

Fundamental Symmetries with Magnetically Trapped ^{82}Rb

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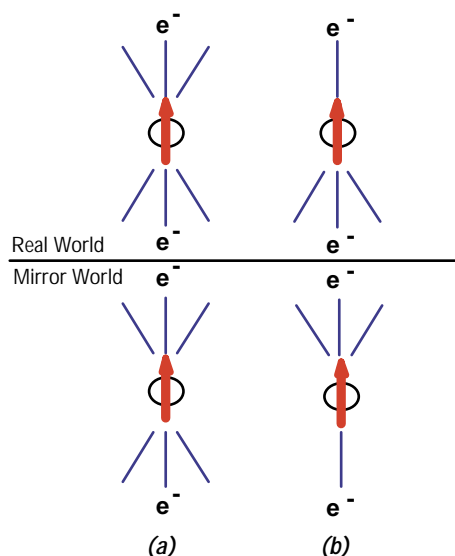


Fig. 1 (a) If parity (or space-reflection symmetry) were preserved in nuclear beta decay, no asymmetry would be detected in the distribution of electrons relative to the spin-orientation of the parent nucleus. In this scenario, the real world and mirror world would be indistinguishable. (b) Due to parity violation, electrons observed in nature exhibit an asymmetry in their angular correlation with the nuclear spin direction.

Theories of fundamental processes develop in tandem with our understanding of symmetry principles and the invariance of physical laws under specific transformations in space and time. Of the four fundamental forces in nature (strong, electromagnetic, weak, and gravity), the weak interaction is unique in that it violates parity, or space-reflection, symmetry. Four decades have passed since the first suggestion by Lee and Yang that parity could be violated in weak interactions,¹ and the subsequent discovery by Wu *et al.* of parity violation in the beta decay of polarized cobalt-60 (^{60}Co).² Today, maximal violation of parity is described in the standard model by a universal interaction between leptons and quarks. This model is based on empirical data established by nuclear and particle physics experiments during the second half of this century. Nonetheless, the origin of parity violation and how it is related to other conservation laws and physical processes is unresolved and marks one of the central mysteries of modern physics. Within the framework of modern gauge theories, an underlying theme speaks of spontaneously broken symmetries wherein discrete symmetries, such as parity, are restored at higher energy scales. Low-energy physics experiments that exploit nuclear beta decay continue to offer a means to probe the fundamental origin of parity violation and, more generally, the helicity structure of the weak interaction.³

Parity violation is manifest in nuclear beta decay as an asymmetry in the angular distribution of beta particles emitted relative to the spin orientation of the parent nucleus (see Fig. 1). In pure Gamov-Teller (GT) transitions, wherein the nucleus undergoes a change in angular momentum by one unit, the electrons are emitted preferentially in a direction opposite to the spin of the parent nucleus. Furthermore, since both the electron and the neutrino emerging from the decay must each carry away one-half unit of angular momentum (intrinsic spin) it follows that the electron must carry off its spin angular momentum aligned anti-parallel to its direction of motion. In other words, the weak interaction is *left-handed*. These, and other, observations have culminated in what we now call the standard model of weak interactions that couples leptons and quarks according to the famous vector-axial vector (V-A) prescription.

The pure GT transitions still offer the most direct route to study parity violation because they proceed solely through the axial-vector couplings responsible for parity violation. Historically, however, studies of pure GT transitions have been limited for lack of good candidates, namely reasonably long-lived and unhindered transitions. Hindered (as opposed to allowed) transitions exhibit energy-dependent behavior beyond the standard (allowed) beta spectrum, which can complicate the analysis of a precision experiment. Technical difficulties have also limited the degree of absolute nuclear polarization achievable to about 60–70%. Because uncertainty in polarization is directly reflected as an uncertainty in the correlation coefficient being measured, it is desirable to design

experiments where polarization arbitrarily close to 100% can be obtained. In addition, experiments making use of solid sources are limited by the difficulties in understanding electron scattering and energy loss effects that can masquerade as a false asymmetry. For these reasons there is little hope of breaching the 1% precision level in the study of pure GT decays using conventional techniques, and one is forced to look to new technologies to improve the situation. It is now possible to envision a new generation of pure GT experiments by exploiting optical and magnetic traps for radioactive atoms.

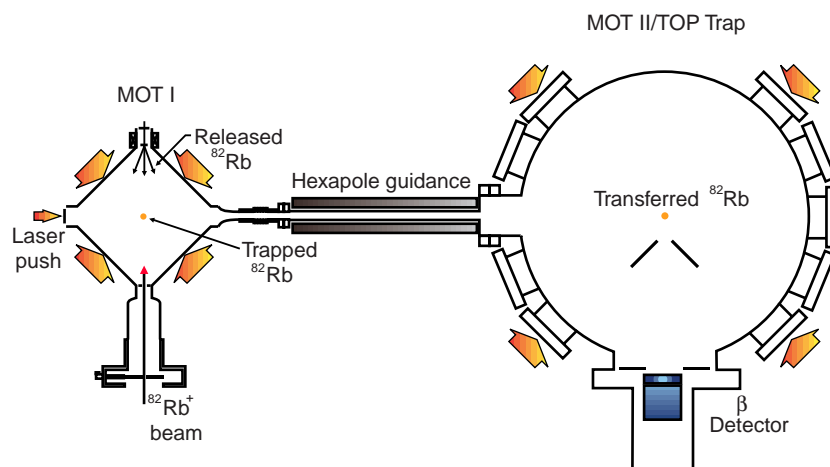
Our research aims specifically at exploiting magnetically trapped rubidium-82 (^{82}Rb) in a new generation of fundamental symmetry experiments. ^{82}Rb , a pure and allowed GT beta decay nucleus, has the appropriate atomic structure and lifetime (75 seconds) to be exploited in a magneto-optical trap. A prototype experiment has been mounted to measure the positron-spin correlation coefficient (A) from polarized ^{82}Rb in a magnetic TOP (time-orbiting potential) trap. In a TOP trap, an essentially massless source of highly polarized ^{82}Rb atoms is suspended in vacuum in the form of a localized cloud ~ 1 mm in diameter, and the direction of the magnetic bias field aligning the nuclear spin rotates uniformly in a plane.⁴ We propose to exploit this rotating beacon of spin-polarized ^{82}Rb nuclei to measure the parity-violating correlation as a continuous function of the positron energy and emission angle relative to the nuclear spin orientation. The positron spin correlation function can be defined,

$$\chi(E, \Theta) = AP\beta(E)\cos\Theta,$$

where E is the electron energy, $\beta(E)$ its velocity relative to light, Θ the angle between the electron momentum vector and the nuclear spin orientation, and P the polarization of the parent nucleus. We are planning an experiment to measure, on an event-by-event basis, the energy of the positron registered in a plastic scintillator, which will allow the determination of $\beta(E)$. Together with a snapshot of the magnetic field configuration, this will allow us to reconstruct the angle of the nuclear polarization vector relative to the momentum vector of the emitted positron ($\cos\Theta$).

While several groups are pursuing fundamental weak-interaction experiments with trapped atoms, the challenge remains to harness sufficient numbers to undertake a meaningful experiment. ^{82}Rb is the daughter product following electron-capture of the parent, strontium-82 (^{82}Sr). The ^{82}Sr source is produced at the isotope production facility of the Los Alamos Neutron Scattering Center (LANSCE) by 750-MeV proton irradiation of a molybdenum target. The strontium sample is then handled at the Chemical Science and Technology (CST) Division's hot cell, where the target is dissolved in hydrogen peroxide and the strontium fraction is extracted using an ion-exchange column. The ^{82}Rb is electrostatically extracted from an ^{82}Sr ion source via a mass separator, where it is implanted into an yttrium foil. The ^{82}Rb is then released as a

Fig. 2 Schematic diagram of the apparatus used to trap, transfer, and retrap ^{82}Rb atoms.



neutral atom by heating the foil, and it is subsequently released to a magneto-optical trap (MOT-I), as shown in Fig. 2. The neutral ^{82}Rb ions are trapped in MOT-I and confined to a 1-mm-diameter cloud at the center of a glass cell. Using an optical push-beam, the ^{82}Rb atoms are then transferred through a hexapole guide tube to a second magneto-optical trap (MOT-II). In MOT-II, they are trapped in a vacuum chamber housing the positron detector hardware. MOT-II is implemented with a set of magnetic bias coils, which are used to polarize the ^{82}Rb atoms in the TOP-trap configuration. The TOP-trap is rapidly switched on such that the direction of the magnetic bias field aligning the nuclear spin rotates uniformly in a plane. The rotating, spin-polarized ^{82}Rb nuclei can then be used to measure the parity-violating correlation.

With an ^{82}Rb ion source, mass separator, and MOT in place, we have demonstrated a world record by trapping several million radioactive ^{82}Rb atoms.⁵ Fig. 3 summarizes the data from these experiments. We have also demonstrated a transfer efficiency of 50% in loading the atoms into MOT-II, where the ultra-high vacuum environment provides a trapping lifetime of 500 seconds. The combination of the large trapping numbers and long trapping lifetime makes us well poised to accumulate sufficient statistics for a precision experiment.

Design of the TOP trap for fundamental symmetry investigations has posed a significant challenge. Large magnetic fields are required to achieve sufficient global polarization of the atom cloud while, at the same time, care must be taken to ensure that energy-dependent magnetic acceptance effects do not produce a false positron-spin asymmetry. Extensive Monte Carlo simulations have been implemented for the design and construction of the TOP trap to minimize systematic effects, and the hardware, including a first generation positron-telescope, are in place. We have only just begun to fully exercise our TOP trap and anticipate performing prototype measurements of the positron-spin correlation function during the coming months.

Prototype experiments will be geared to address a number of experimental details to assess our ultimate sensitivity in measuring

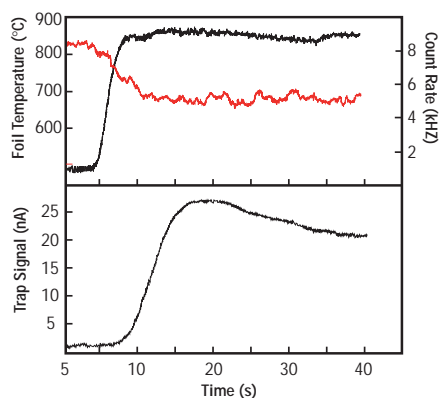


Fig. 3 Data recorded while trapping ^{82}Rb atoms in MOT-I. The top panel shows the release of atoms from the yttrium foil (red curve) upon heating the foil to a temperature of 850°C (black-curve). The lower panel shows the modulated fluorescence signal as measured with a photomultiplier and lock-in amplifier (blue-curve) as atoms are trapped at the center of MOT-I. The peak signal of 25 nA corresponds to a trapping signal of some six million radioactive atoms, and the characteristic half-life of ^{82}Rb is observed as the radioactive atoms decay.

the positron-spin correlation coefficient. Perhaps the most challenging detail facing us is in our ability to ascertain the absolute polarization of the atom cloud. With systematic issues under control, the ultimate sensitivity of the experiment could be limited at the 0.5% level of accuracy due to energy-dependent, recoil-order corrections that are complicated by nuclear structure in complex nuclei. It is possible, however, to recover the recoil-order correction in a novel manner by exploiting both the asymmetry and higher multipole anisotropy terms. Both terms are available in our experiment since the correlation function can be mapped out as a continuous function of both positron energy and emission angle. In this way, the data could be exploited in the search for physics beyond the standard model while extracting the recoil-order corrections experimentally and without reliance on difficult and inaccurate calculations.

We have an opportunity at Los Alamos to play an active and lead role in the next generation of fundamental symmetry experiments that exploit trapped radioactive atoms. The combination of nuclear chemistry and atomic, nuclear, and particle physics capabilities inherent in this collaboration gives us a unique potential for precision and world-class experiments that are unlikely to take place anywhere else in the world in the foreseeable future. Indeed, the success of the proposed experiment would mark the first fundamental nuclear physics experiment that exploits a TOP-trap and the first effort to measure the positron-spin correlation as a continuous function of positron energy and emission angle.

References

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